Language-level Transactions for Modular Reliable Systems

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The transaction model is a natural means to express atomicity, fault-tolerance, synchronization, and exception handling in reliable programs. A (lightweight, in-memory) transaction can be thought of as a sequence of program loads and stores which either ***commits*** or ***aborts***. If a transaction commits, then all of the loads and stores appear to have run atomically with respect to other transactions. That is, the transaction's operations appear not to have been interleaved with those of other transactions or non-transactional code. If a transaction aborts, then none of its stores take effect and the transaction can be safely restarted, typically using a backoff algorithm to preclude live-lock. A subset of the traditional ACID database semantics are provided.

Although transactions can be implemented using mutual exclusion (locks), we present algorithms utilizing non-blocking synchronization to exploit optimistic concurrency among transactions and provide fault-tolerance. A process which fails while holding a lock within a critical region can prevent all other non-failing processes from ever making progress. It is in general not possible to restore the locked data structures to a consistent state after such a failure. Non-blocking synchronization offers a graceful solution to this problem, as non-progress or failure of any one thread or module will not affect the progress or consistency of other threads or the system.

Implementing transactions using non-blocking synchronization offers performance benefits as well. Even in a failure-free system, page faults, cache misses, context switches, I/O, and other unpredictable events may result in delays to the entire system when mutual exclusion is used to guarantee the atomicity of operation sequences; non-blocking synchronization allows undelayed processes or processors to continue to make progress. Similarly, in real-time systems, the use of non-blocking synchronization can prevent *priority inversion* in the system by allowing high priority threads to abort lower priority threads at any point.

We show how to integrate non-blocking transactions into an object-oriented language, "transactifying" existing code to fix existing concurrency bugs and using transactions for modular fault-tolerance, backtracking, exception-handling, and concurrency control in new programs.

We propose the use of compiler-supported "atomic" blocks to specify synchronization. This is less error-prone than manual maintenance of a locking discipline: deadlocks may be introduced when locks are not acquired and released in a highly disciplined manner, and the specification of locking discipline cuts across module boundaries. Races are common when multiple shared objects are involved in an operation, each with its own lock. We provide several examples of such problematic locking code. A non-blocking transaction implementation prevents inadvertent deadlocks, and `atomic` declarations implemented with the transaction mechanism can extend across method invocations and module boundaries to protect multiple objects involved in an operation without allowing races between them. An optimistic non-blocking implementation provides performance improvements over locking strategies in some cases as well.

Language-level transactions are used as a general exception-handling and backtracking mechanism. Instead of forcing the programmer to manually track changes made to program state in order to implement proper fault recovery, we can handle the exception using transaction rollback to automatically restore a safe program state, even if the fault occurred in the middle of mutating shared objects. An efficient and graceful transaction mechanism integrated into the programming language encourages a robust programming style where recovery and retry after an unexpected condition is made simple and faults and recovery do not break abstraction boundaries.

We describe an efficient pure-software transaction mechanism we have implemented for programs written in Java. We also discuss our design and simulation (with Asanović, Kuszmaul, Leiserson, and Lie) of minimally-intrusive architecture extensions which allow most transactions to complete with near-zero overhead. Unlike previous hardware approaches, our scheme is scalable and supports transactions of unlimited size, although performance is best for transactions which fit in local cache. Finally, we describe our hybrid hardware-software scheme combining the speed hardware provides for small transactions with the flexibility the software implementation allows for large or long-lived transactions.

Integrating transactions into the programming language and implementing them with the high-efficiency techniques described enables the creation of software with higher reliability. Synchronization is more robust and its specification is modular and less error-prone, and faults and exceptions in general can be soundly handled with low overhead using the transaction mechanism.

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Outline

- **Problems with traditional software development**
  - lock ordering
  - proper atomicity
  - fault-tolerance
  - priority inversion
- Language-level Transactions
- How?
  - Software implementation
  - Hardware implementation
  - Both!
- Conclusions

Programming Reliable Systems (is hard)

Conventional Locking: Ordering

- When more than one object is involved in a critical region, **deadlocks may occur**!
  - Thread 1 grabs A then tries to grab B
  - Thread 2 grabs B then tries to grab A
  - No progress possible!
- **Solution: all locks ordered**
  - A before B
  - Thread 1 grabs A then B
  - Thread 2 grabs A then B
  - No deadlock

Conventional Locking: Ordering

- Maintaining lock order is a lot of work!
- Programmer must choose, document, and rigorously adhere to a **global** locking protocol for each object type
  - development overhead!
- All symmetric locked objects must include lock order field, which must be assigned uniquely
  - space overhead!
- Every multi-object lock operation must include proper conditionals
  - which lock do I take first? which do I take next?
  - execution-time overhead!
- ***No exceptions!***

Multi-object atomic update

- Programmer's mental model of locks can be faulty
- **Monitor synchronization**: associates locks with objects
- Promises modularity: locking code stays with encapsulated object implementation
- Often breaks down for multiple-object scenarios
- End result: **unreliable software, broken modularity**

A problem with multiple objects

```
public final class StringBuffer ... {
  private char value[ ];
  private int count;
  ...
  public synchronized StringBuffer append(StringBuffer sb) {
    ...
A:int len = sb.length();
    int newcount = count + len;
    if (newcount > value.length)
      expandCapacity(newcount);
    // next statement may use state len
B:sb.getChars(0, len, value, count);
    count = newcount;
    return this;
  }
  public synchronized int length() { return count; }
  public synchronized void getChars(...) { ... }
}
```

Fault-tolerance

- Locks are **irreversible**
- When a thread fails holding a lock, the system will crash
  - it's only a matter of time before someone else attempts to grab that lock
- What are the proper semantics for exceptions thrown within a critical region?
  - data structure consistency not guaranteed
- Asynchronous exceptions?

Priority Inversion

- Well-known problem with locks
- Described by Lampson/Redell in 1980 (Mesa)
- Mars Pathfinder in 1997, etc, etc, etc
- Low-priority task takes a lock needed by a high-priority task -> the high priority task must wait!
- Clumsy solution: the low priority task must become high priority
- What if the low priority task takes a long time?

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Programming Reliable Systems (is easy?)

Language-level Transactions

- **Locks are the wrong model for expressing synchronization!**
- **Atomicity is a more natural (and modular) way to specifying the system**
- **Let's use transactions to implement atomic regions**
- **What sort of transactions do we want?**

Transactions (definition)

- A transaction is a sequence of loads and stores that either **commits** or **aborts**
- If a transaction commits, all the loads and stores appear to have executed **atomically**
- If a transaction aborts, none of its stores take effect
- Transaction operations aren't visible until they commit or abort
- Simplified version of traditional ACID database transactions (no durability, for example)

Non-blocking synchronization

- Although transactions can be implemented with mutual exclusion (locks), we are interested only in **non-blocking** implementations.
- In a non-blocking implementation, the failure of one process cannot prevent other processes from making progress. This leads to:
  - **Scalable parallelism**
  - **Fault-tolerance**
  - **Safety**: freedom from some problems which require careful bookkeeping with locks, including priority inversion and deadlocks
- Little known requirement: limits on trans. suicide

Making StringBuffer atomic

```
public final class StringBuffer ... {
  private char value[ ];
  private int count;
  ...
  public synchronized StringBuffer append(StringBuffer sb) {
    ...
A:int len = sb.length();
    int newcount = count + len;
    if (newcount > value.length)
      expandCapacity(newcount);
    // next statement may use state len
B:sb.getChars(0, len, value, count);
    count = newcount;
    return this;
  }
  public synchronized int length() { return count; }
  public synchronized void getChars(...) { ... }
}
```

Making StringBuffer atomic

```
public final class StringBuffer ... {
  private char value[ ];
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    // next statement may use state len
B:sb.getChars(0, len, value, count);
    count = newcount;
    return this;
  }
  public atomic int length() { return count; }
  public atomic void getChars(...) { ... }
}
```

Solving the lock ordering problem

```
void pushFlow(Vertex v1, Vertex v2, double flow) {
  v1.excess -= flow; /* Move excess flow from v1 */
  v2.excess += flow; /* ...to v2 */
}
```

- Simple **network flow algorithm**
- “Flow” moved from node to node in the graph
- Updates to **two different objects**
- Serial version above requires a complicated parallel version when using locks

Solving the lock ordering problem

```
void pushFlow(Vertex v1, Vertex v2, double flow) {
  v1.excess -= flow; /* Move excess flow from v1 */
  v2.excess += flow; /* ...to v2 */
}

void pushFlow(Vertex v1, Vertex v2, double flow) {
  Object lock1, lock2;
  if (v1.id < v2.id) { /* avoid deadlock */
    lock1 = v1; lock2 = v2;
  } else {
    lock1 = v2; lock2 = v1;
  }
  synchronized (lock1) {
    synchronized (lock2) {
      v1.excess -= flow; /* Move excess flow from v1 */
      v2.excess += flow; /* ...to v2 */
    }
  }
}
```

Solving the lock ordering problem

```
void pushFlow(Vertex v1, Vertex v2, double flow) {
  v1.excess -= flow; /* Move excess flow from v1 */
  v2.excess += flow; /* ...to v2 */
}
```

```
void pushFlow(Vertex v1, Vertex v2, double flow) {
  atomic {
    v1.excess -= flow; /* Move excess flow from v1 */
    v2.excess += flow; /* ...to v2 */
  }
}
```

- **Specifying desired atomicity property directly is much simpler for the programmer!**

Addressing reliability, fault tolerance, and priority inversion

- A proper implementation of the transaction mechanism allows **constant-time abort**
  - Allows us to solve priority inversion by aborting the low-priority thread!
- Atomicity properties are **modular** – no global lock ordering required
- A **reasonable semantics for exceptions**: critical region aborted/undone. No dangling locks.
- Failure of one thread will not cause the system to fail!

Programming Reliable Systems (is hard)

- Problems with traditional software development
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  - proper atomicity
  - fault-tolerance
  - priority inversion
- Language-level Transactions
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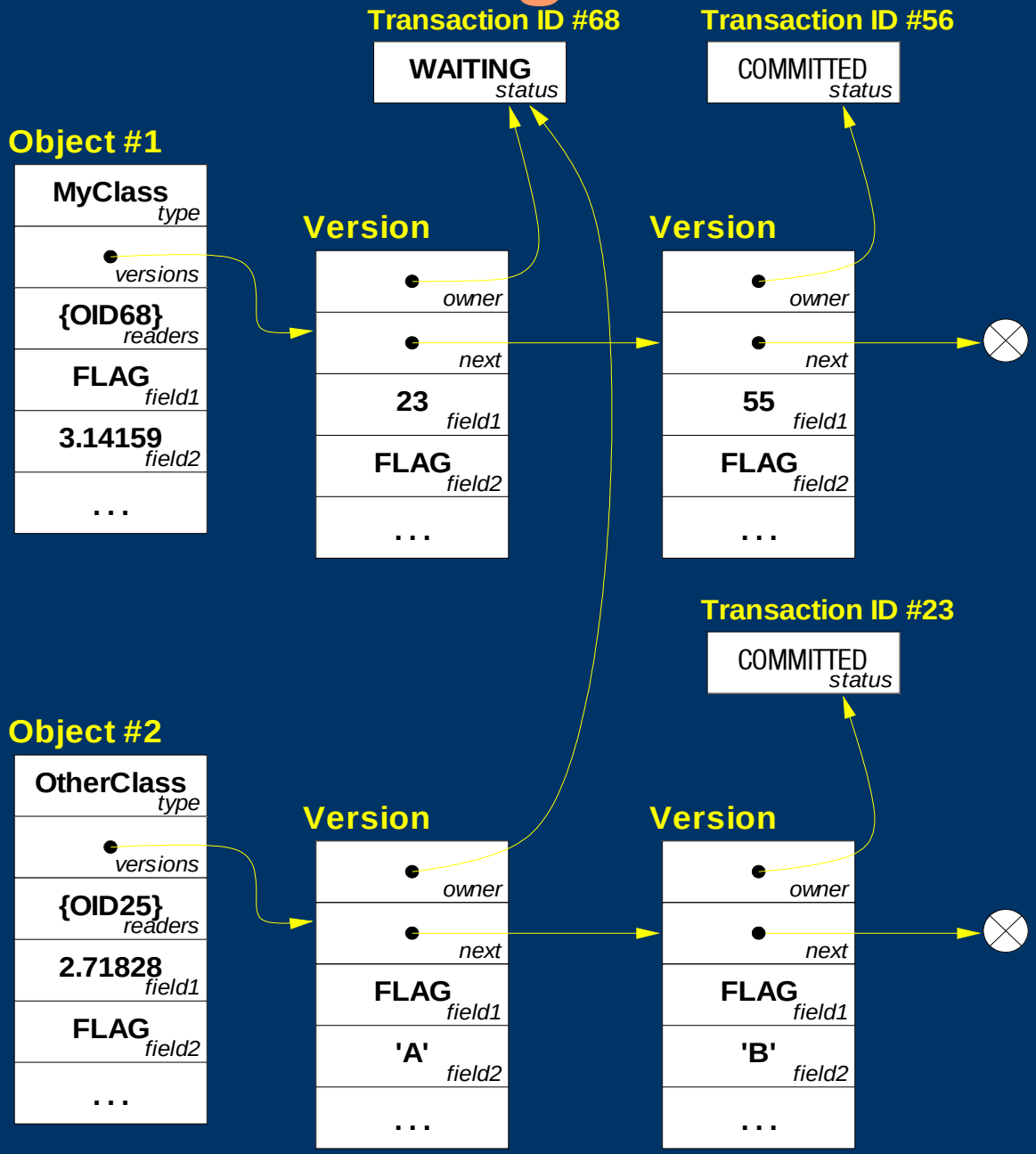
Software Transaction Implementation

- **Goals:**
  - Non-transactional operations should be fast
  - Reads should be faster than writes
  - Minimal amount of object bloat
- **Solution:**
  - Use special `FLAG` value to indicate "location involved in a transaction"
  - Object points to a linked list of **versions**, containing values written by (in-progress, committed, or aborted) transactions
  - Semantic value of `FLAG`ged field is: "value of the first version owned by a committed transaction on the version list"
  - Values which are "really" FLAG are handled with an escape mechanism

Transactions using version lists



Performance

- Non-transactional code only needs to check whether a memory operand is `FLAG` before continuing.
  - On superscalar processors, there are plenty of extra functional units to do the check
  - The branch is extremely predictable
  - This gives only a few % slowdown
- Once `FLAG`ged, transactional code operates directly on the object's "version"
- Creating versions can be an issue for large arrays; use "functional array" techniques

Non-blocking algorithms are hard!

- In published work on Synthesis, a non-blocking operating system implementation, three separate races were found:
  - One **ABA problem** in LIFO stack
  - One **likely race** in MP-SC FIFO queue
  - One **interesting corner case** in quaject callback handling
- It's hard to get these right! Ad hoc reasoning doesn't cut it.
- Non-blocking algorithms are too hard for the programmer
- Let's get it right **once** (and verify this!)

The Spin Model Checker

- Spin is a **model checker** for communicating concurrent processes. It checks:
  - Safety/termination properties
  - Liveness/deadlock properties
  - Path assertions (requirements/never claims)
- It works on **finite** models, written the Promela language, which describe **infinite** executions.
- Explores the **entire state space** of the model, including all possible concurrent executions, verifying that Bad Things don't happen.
- Not an absolute proof – pretty useful in practice
- **Make systems reliable by concentrating complexity in a verifiable component**

Spin theory

- Generates a **Büchi Automaton** from the Promela specification.
  - Finite-state machine w/ special acceptance conditions
  - Transitions correspond to executability of statements
- **Depth-first search of state space**, with each state stored in a hashtable to detect cycles and prevent duplication of work
  - If *x* followed by *y* leads to the same state as *y* followed by *x*, will not re-traverse the succeeding steps
- If memory is not sufficient to hold all states, may **ignore hashtable collisions**: requires one bit per entry. # collisions provides approximate coverage metric

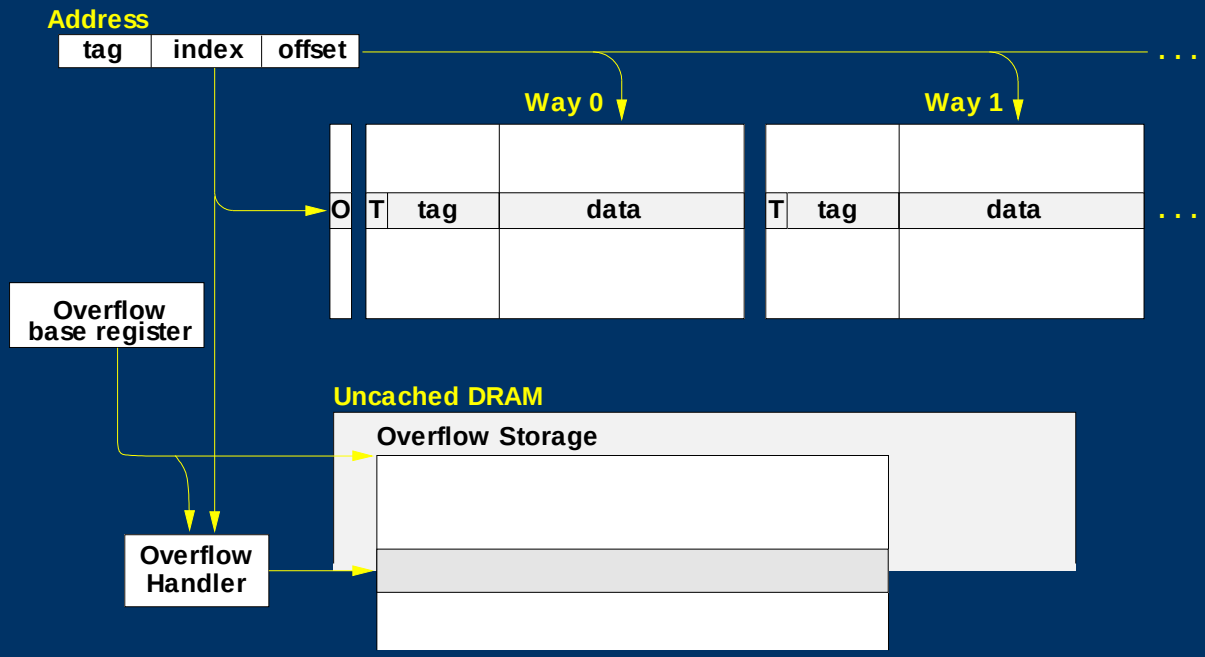
Verified Software Transactions

- **Modelled the software transaction implementation in Promela**
- **Low-level model – every memory operation represented**
- **Spin used 16G of memory to exhaustively verify the implementation within a 6-version 2-object scope.**

Hardware Implementation

- Following earlier work by Knight '86, Herlihy and Moss '92, '93
- Cache is used to store uncommitted transactional state (marked with a T bit)
- Main memory contains 'backup state'
- Cache-coherence protocol extended to coordinate transactions
- Our recent work (Ananian, Asanović, Kuszmaul, Leiserson, Lie HPCA 2005) overcomes transaction-size limitations in earlier designs
- Near-zero performance overhead.
  - Piggy-backs on existing cache coherency traffic

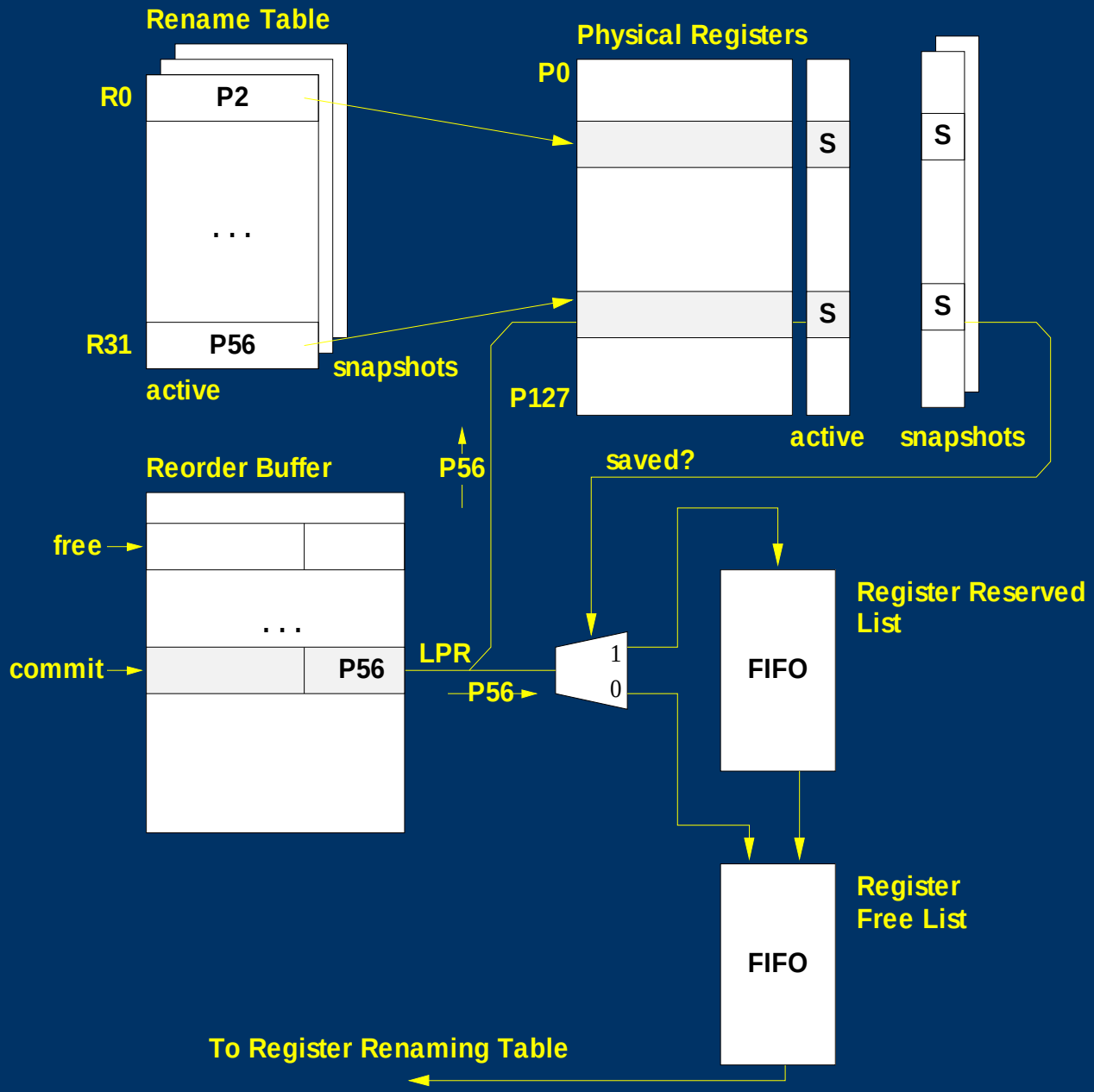
Hardware Transaction Cache Organization



- Each cache line gets a “T” bit indicating that this line is involved in a transaction
- On abort, “T” lines are invalidated
- On commit, the T bits are cleared
- Overflow mechanism

Register File Modifications

- Minor modifications to the processor rename table to support register restore after transaction abort.

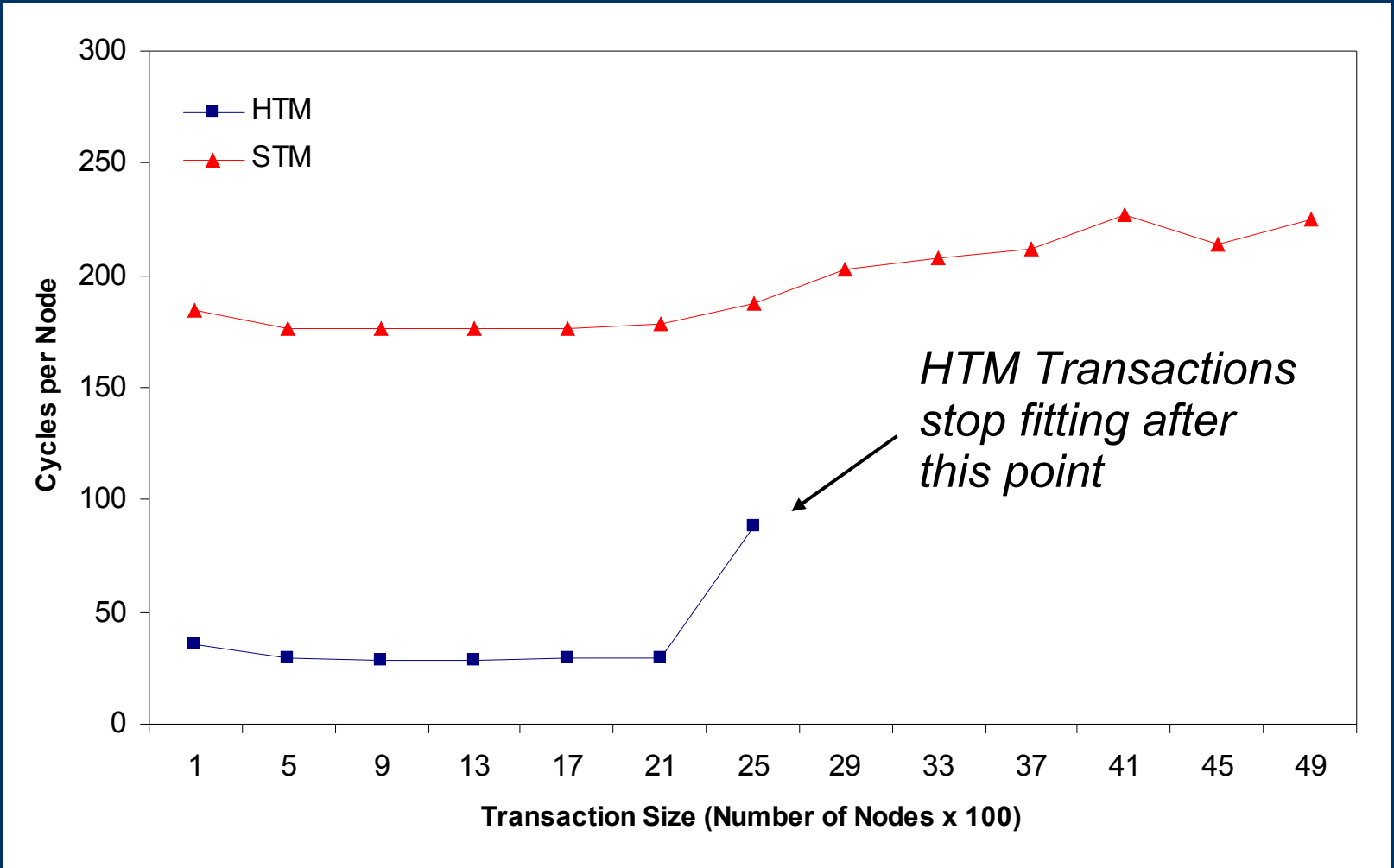


Hardware/Software Implementation

- Hardware transaction implementation is very fast! But it is limited:
  - Slow once you exceed Cache capacity
  - Transaction lifetime limits (context switches)
  - Limited semantic flexibility (nesting, etc)
- Software transaction implementation is unlimited and very flexible!
  - But transactions may be slow
- **Solution: failover from hardware to software**
  - Simplest mechanism: after first hardware abort, execute transaction in software
  - Need to ensure that the two algorithms play nicely with each other (consistent views)

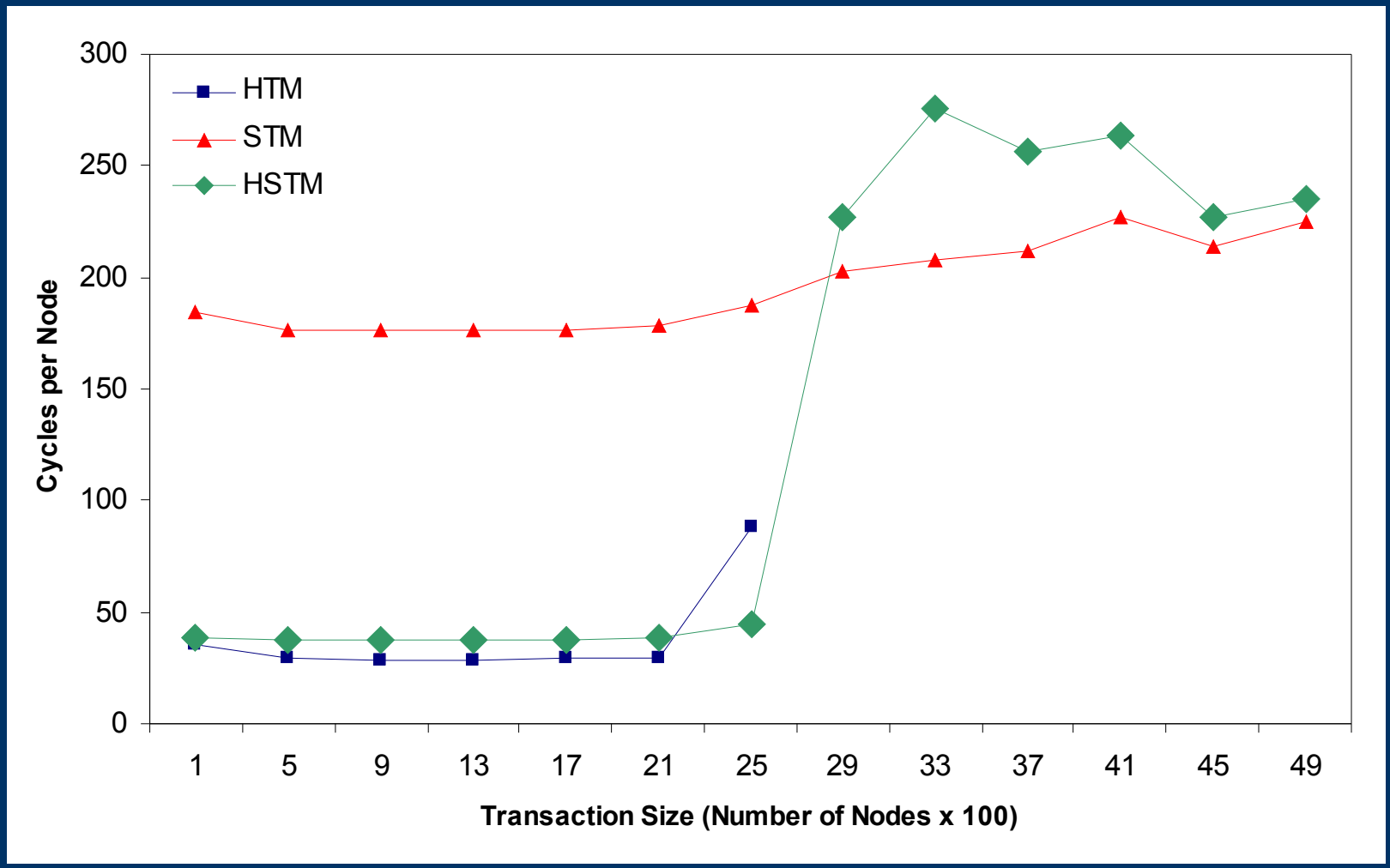
Overcoming HW size limitations

- Simple node-push benchmark
- As xaction size increases, we eventually run out of cache space in the HW transaction scheme



Overcoming HW size limitations

- Simple node-push benchmark
- **Hybrid scheme best of both worlds!**



Conclusions

- **Language-level transactions provide a more-modular way to build reliable concurrent systems.**
- **Transactions can reduce software complexity and eliminate common programmer mistakes**
- **We've implemented a transaction mechanism for Java programs using software, hardware, and (in progress) joint approaches using the FLEX compiler infrastructure.**
- **Transactions can be efficient and practical to use!**